## Project Title

Due Date:

Name:

Course:

Instructor:

**Abstract**

This report involves simulating a four loop Pressurized Water Reactor (PWR) using a numerical loop momentum balancing approach. The first section details the theoretical basis for the pressurized water reactor and how the momentum balancing equations provide an accurate approximation for the reactor physics. Next, the report dives into the specific methods used in order to discretize the momentum balance equations for the specific four loop PWR before determining the appropriate Reactor Coolant Pump (RCP) and Steam Generator design parameters needed to meet required mass flux and core inlet temperature rises. This reactor is then analyzed for performance in three pump transients. The first transient evaluates performance in a loss of all AC casualty where all RCPs trip off simultaneously. The second evaluates a locked rotor casualty impacting a single loop, where the loop effectively loses all flow. The third transient analyzes a single RCP shear inducing reverse flow through the associated loop. Finally, the number of clogged steam generator tubes are adjusted to determine the proportion required to reduce mass flow rates by 10% of steady state.

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# Introduction and Theory

This report analyses many reactor safety considerations which are involved in designing a pressurized water reactor (PWR). PWRs are common in the nuclear power industry, so analyzing this design provides insight into limiting casualties, reactor safety concerns, and the importance of proper reactor plant design. The specific geometry analyzed in this report involves a four loop PWR, where each loop has a Reactor Coolant Pump (RCP), a steam generator, and no check valves to prevent backwards flow. Loop one is used to determine the transient behavior, and the other three loops are grouped into a set of symmetric loops collectively referred to as loop two. A visual depiction of the PWR is seen in the figure below:

A diagram of a building

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Figure 1: Visualization of PWR Nodes

Where the node categorization is given by the following table:

A table with text and numbers

Description automatically generated

Before discussing the results of the transients performed as part of this report, it is important to understand the theory used to numerically model the PWR. Fundamentally, this report calculates the mass flow rate by ensuring momentum is conserved within the reactor. As the heat transfer from both the steam generator and fuel rods depend on the mass flow rate, the flow rate is used to determine the current fluid internal energy and temperatures in the PWR loops and core. While these equations are continuous, this report discretizes the momentum and internal energy at each node shown in Figure 1, which assumes homogenous properties in each node. This report sizes the RCPs and Steam Generators to meet minimum required mass flow rates and core inlet temperatures. Afterward, it analyzes the impact of various transients important for reactor safety on overall reactor performance. The first transient evaluates performance in a loss of all AC casualty where all RCPs trip off simultaneously. The second evaluates a locked rotor casualty impacting a single loop, where the loop effectively loses all flow. The third transient analyzes a single RCP shear inducing reverse flow through the associated loop. The final transient analyzes the number of clogged steam generator tubes required to reduce mass flow rates by 10%.

Also includes project objectives.

Typically, the project report can be between 10 to 30 pages long. Grading will be focused on content, logic, and not the size of the report.

# Methods

Momentum Conservation

As momentum is conserved within the reactor, any momentum going into a node must either exit the node or be stored within it. This report models the momentum in each node using the below linearized equations:

A math equations on a white background

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In the above equations, m is the mass flow rate, L is the length of the node, A is the node’s cross-sectional area, D is the node’s equivalent diameter, k is the minor friction losses, f is the Colebrook friction factor, ρ is the water density, and ∆H is the change in height over the node. As the timestep advances, this momentum balance equation is solved for the node’s mass flow rate at time t+∆t by solving the below matrix equation.

A number and a number of numbers

Description automatically generated with medium confidence

This is implemented in the code below, where the step\_massflux function takes in the model parameters, loop nodes, and core nodes and then iterates through the above momentum equations to solve for the new mass flux values and pressure drop across the core. Each loop and core object have their own momentum method to determine the a and b coefficients:

A computer screen with white text

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A computer screen shot of a code

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After the mass flow rate has been updated for the new time step, the corresponding pump differential pressure is calculated through the following pump curve:

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Internal Energy

As the mass flow rate in each node changes to conserve momentum, the internal energy and corresponding bulk fluid temperature will also change. This behavior is modeled by determining the new equilibrium internal energy at each node with the new equilibrium mass flow rates through the below equation:

A math equations and formulas

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Here, V is the node volume, q is the heat flux into the fluid from the node (positive for heat flowing into the fluid), and u is the node’s internal energy. There are several methods which can be used to solve the momentum and internal energy equation. In developing the numerical simulation two different methods were investigated – a Newton-Raphson solver and a direct iterative solver. The Newton-Raphson solver takes in a matrix of equations, determines the associated Jacobian matrix, and then solves for new minimum input values based on the derivatives calculated in the Jacobian. The direct iterative solver updates individual inputs based on information from the previously calculated inputs. This process repeats until the individual inputs converge on the steady state values. Below is the implementation of the Newton-Raphson method.

A screen shot of a computer program

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However, this method was not as well behaved as the direct iterative implementation. The direct iterative method solves the internal energy equation directly for the new internal energy at time t+∆t as seen below:

A black and white math symbols

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This equation was solved continually by updating the internal energy at each time step based on the incoming mass flux and internal energy until a steady state was reached. This approach eliminated the need to solve all internal energy equations simultaneously. In order to reach convergence with small internal energy differences as a result of large mass flow rates, the internal energy was round to four decimal places after each iteration. This project used the direct iterative approach to solve for the internal energy at each node after each new mass flow rate.

Peak Centerline Temperature

In order to determine the maximum surface temperature of the cladding, one dimensional PCT equations were solved based on the current heat flux from the corresponding core node. The Weisman correlation was used to determine appropriate heat transfer for a square lattice of fuel rods:

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As the assignment required maintaining the maximum surface temperature of the fuel cladding below saturation temperature, only convective heat transfer from single phase flow conditions was analyzed. Based on the heat transfer coefficient between the bulk fluid and the fuel rod, the temperature rise at the surface of the cladding is determined through the below equation and python implementation.

A screen shot of a computer code

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Putting all of the above equations together, the below script was used to advance the run through time steps based on the provided run time (run\_secs). In order to minimize the amount of time required to run the simulation and reach steady state, after finding the steady state condition the state was saved and reloaded for all future transient runs. The steady state condition ran for 13 seconds before transients were inserted into the reactor, and so for all subsequent graphs the transients occur at t=13 seconds.

A computer screen shot of a program code

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# Problem Formulation

Scenario A

This scenario sought to determine the necessary RCP ∆P to meet the provided mass flow rates by adjusting the ∆P Rated value.

Scenario B

To run this transient, all four RCPs were set to trip off after steady state operation. This simulates an electrical casualty which immediately trips off all RCPs. After the pumps trip, they begin to coast down to provide 0 ∆P based on the following formula:

A mathematical equation with black text

Description automatically generated

Where β is dictated by the fly wheel inertia of the pump, and t is the time since the pump trip. For a fly wheel with a high inertia, the pump will take longer to coast down which is signified by a larger β value. After the pumps trip, we assume that the automatic protective system takes two seconds to recognize the loss of flow casualty and scram the plant. This scenario seeks to size the pump such that the associated β will prevent thermal limit violations in this transient.

Scenario C

Tripping off one pump

Scenario D

Locked rotor condition

Scenario E

Reverse flow condition

Scenario F

Minimum SG tubes required to reduce flow rates by 10%

For example, include schematic of the domain, what is being done and how the results are obtained.

# Results and Discussion

Scenario A

In order to meet the required mass flux, the RCP required a ∆P rated of

Scenario B

In this scenario, there are two major concerns. The first involves an immediate temperature rise after the loss of flow event and before the reactor scrams. The reduction in mass flow from the tripped pump causes the coolant to spend more time in the core, greatly increasing the core outlet temperature. Similarly, the hotter coolant increases the PCT calculated in the four core nodes. The goal of this transient was to determine the minimum β value required to ensure that both the core exit and peak cladding temperature do not exceed saturation temperature. The larger the beta, the slower the pump will coast down, the higher the flow rate before the scram, and so the lower A graph of different colored lines

Description automatically generatedthe total temperature rise. Below are the graphs of core exit temperature, PCT, and mass flow:

A graph of a function

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A graph of a line

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Some further discussion

Problem c

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Problem d

A graph of a diagram

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Problem e

This transient was unable to be fully modeled with the current state of the Python simulation. Even once the RCP pump shear occurred to allow reverse flow conditions, the calculated pressure drop across the core was still low enough that the flow preferred to travel up the reactor vessel as opposed to around the downcomer region associated with loop one. This clearly illustrates an error in the implementation of the momentum balancing and internal energy discussion. While the mass flow rate does not appropriately update to reflect the reverse flow through loop one, the rest of the PWR behaves similar to problem c, where there is an initial decrease in flow through the impacted loop. However, this transient sees the mass flow rate increase by a greater proportion after the scram, most likely as a result of the exit loss coefficient of the pump.

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Problem f

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863 clogged tubes

Includes the performed parametric studies and the analysis of the results. This section should include all the tests performed, results and its interpretation.

Specifically, this project requires several specific tasks (see description). Clearly separate the results and discussion for each task

# Conclusions

Discuss problems / issues / good results as well as potential future work. Future work should evaluate reactor safety in longer time domains in order to appropriately factor decay heat removal as a criteria for PWR casualty response.

# References